Final Report: Air-Sea Momentum Coupling and Radar Response at High Winds

M.A. Donelan
Rosenstiel School of Marine & Atmospheric Science, University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
phone: (305) 421-4717 fax: (305) 421-4701 email: mdonelan@rsmas.miami.edu

H.C. Graber
Rosenstiel School of Marine & Atmospheric Science, University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
phone: (305) 421-4935 fax: (305) 421-4701 email: hgraber@rsmas.miami.edu

B. K. Haus
Rosenstiel School of Marine & Atmospheric Science, University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
phone: (305) 421-4932 fax: (305) 421-4701 email: bhaus@rsmas.miami.edu

Award Number: N000140310567

LONG-TERM GOALS

To determine the changes in air-sea frictional drag and normalized radar cross-section at high winds and to investigate the root causes of regime changes in the momentum coupling and the radar response.

OBJECTIVES

- To verify preliminary laboratory experiments showing “saturation” of the drag coefficient and of the radar backscatter at high winds.

- To use the high precision wave follower and an Elliott style pressure probe to measure the pressure very near the water surface in strong winds.

- To measure the surface pressure and slope of wind-generated and paddle-generated waves in high wind conditions.

- To measure the full wavenumber-frequency spectrum in high wind conditions.

- To determine the mechanism for momentum and energy transfer to the waves in various wind speed regimes and thus to elucidate the air-sea coupling mechanisms in high winds.

- To measure the radar cross-section for both HH and VV polarizations at C-band under high wind conditions and to determine the relationship between capillary-gravity wave properties and radar response in these conditions.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Air-Sea Momentum Coupling And Radar Response At High Winds**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Miami,Rosenstiel School of Marine & Atmospheric Science,4600 Rickenbacker Causeway,Miami,FL,33149**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Numerical models of hurricane intensification typically employ bulk coefficients of momentum, heat and moisture to parameterize the driving and dissipative effects of the air-sea coupling. Bulk coefficients based on field measurements typically cover the range of wind speeds of 5 to 20 m/s. (Much above this range the data is too sparse to produce reliable estimates of statistically variable turbulence quantities.) In this range the data show a linear increase of the bulk coefficient for momentum (the drag coefficient), while the heat and moisture coefficients appear to be constant. Extrapolation of the bulk estimates to higher wind speeds leads to the conclusion that typical tropical warm oceans cannot sustain hurricanes of the strength observed, i.e., categories 4 and 5 hurricanes would not occur. This raised the question of the appropriateness of the application of existing bulk models to high winds. This project explored whether the drag coefficient "saturates" at high winds. We employed the University of Miami's Air-Sea Interaction Saltwater Tank (ASIST) to explore the effect of high winds on the air-sea momentum, heat and moisture coupling. At the maximum speed wave breaking is intense and the tops of the wave crests are blown into spume. This facility was acquired through DURIP grant number N00014-98-1-0261.

WORK COMPLETED

I. Measurements of the aerodynamic drag coefficient and radar response in high winds.

A series of measurements of the aerodynamic drag coefficient were made in equivalent 10-m wind speeds up to 53 m/s. Several approaches to measuring the total momentum transfer were employed to provide confidence that the techniques employed were appropriate:

1. Direct Reynolds stress measurements using hot-film anemometry. This approach was limited to winds in which the concentration of spray in the air was low.

2. Momentum balance on the air side including the horizontal gradient of pressure, wall stress on the walls and ceiling, changes in the velocity profile.

3. Momentum balance on the water side including the set-up of the surface, horizontal pressure gradient in the air ("inverted barometer effect") bottom stress.

4. Velocity profile measurements using the "law of the wall" to deduce the stress.

The approach to measuring σ_o was as follows:

The radar response (σ_o) was measured with our in-house dual polarized C-Band scatterometer at various incidence angles. The scatterometer was mounted on a rotating arm so that its range was kept constant as the incidence angle was changed. The radar radiates a patch of the surface about 10 cm in diameter. The radiated patch was in the center of the area imaged by a 2-D imaging slope gauge and just downwind from a triplet of laser elevation gauges. The imaging slope gauge covers an area of 30 cm by 20 cm (downwind by crosswind) with a resolution of 0.5 mm by 0.8 mm. It allowed us to view the Bragg scatterers in detail and also to relate them to the slopes of the longer wind waves and paddle waves. The imaging slope gauge has a maximum sampling rate of 120 Hz.

II. Pressure-slope measurements in high winds

A series of 10-minute runs with different wind speeds and mechanical waves were conducted in ASIST. The equivalent 10-m wind speed derived from a log-profile, ranged from 0-23 m/s. Mechanical waves of frequency 1-hz and 0.3 cm amplitude traveling in the wind direction were generated.

The main challenge of the experiment was to acquire the water elevation signal, process it and send to a linear motor to repeat the shape of the wave in on-line mode. Any time lag would shift pressure probe and water surface motion synchronization (fig.3). For that reason a 'laser elevation gauge' technique was used to measure surface elevation and slope: three laser beams were vertically placed under the pressure probe (fig.2). Light intensity along each laser beam was measured by a line scan camera. Fluorescence added to the water caused a sharp transition in beam brightness as it went through the water surface. The vertical location of this transition was retrieved from the line scan camera data by a Labview code and sent to a servo line motor controller to follow.

At high wind speeds the water surface becomes rough and the surface elevation acceleration becomes strong enough to create an additional pressure in tubes between probes and pressure transducers of the order of the measured pressure. For that reason the pressure transducers had to be placed inside the tank, on the moving part of the follower as close to the probes as possible. Measurements were successfully made up to a wind speed (converted to 10-m using a log-profile) of 21.6 m/s.

RESULTS

I. Drag coefficient saturation in very high winds

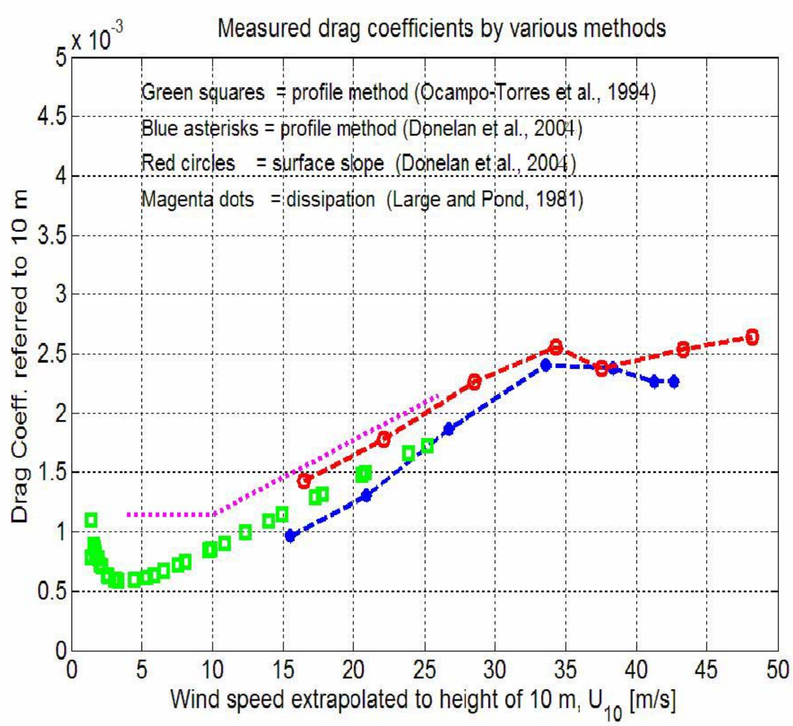

Figure 1. Measured drag coefficients in high winds. From Donelan et. al. 2004.

Figure 1 (from Donelan et al., 2004) shows the drag coefficients estimated via methods 1, 3 and 4 (above). In addition data from another laboratory tank were added to cover the lower wind speeds. In all cases the wind speed and drag coefficients were extrapolated to the standard 10-m height. The measured drag coefficients display the characteristic reduction with wind speed at very low winds corresponding to smooth flow, i.e., viscous drag. Above 5 m/s the effects of form drag (rough flow) become apparent and the drag coefficient shows a steady increase with wind speed. The conventional view (e.g., Large and Pond, 1981) suggests that the drag coefficient keeps on increasing with wind speed. Our results, shown in Figure 1, are indicative of a rapid "saturation" of the drag coefficient at about 33 m/s. There seems to be a "regime change" in the aerodynamic characteristics of the flow at these high speeds. Indications are that the continuous (observed) breaking of the largest waves leads to a quasi-permanent separation bubble in the wake of the breaking crests so that the external flow does not penetrate to the troughs and instead flows over a surface that appears to aerodynamically smoother than it is in the absence of separation. We may call this regime "sheltered flow".

The microwave reflectivity measurements in ASIST indicated that the geometric roughness of the short (centimetric) waves also decreased at sufficiently high wind speeds. Figure 2 shows the microwave cross section measured in the tank at C-band (5.3 GHz) looking upwind at a 35^{o} incidence angle. The microwave cross section is a direct measure of the small-scale surface roughness. Figure 2 shows that the cross section reaches a maximum at the wind speed where the drag coefficient stops increasing. The behaviour of the cross section indicates that the small-scale geometric roughness is not continuing to increase with wind speed. When the outer flow no longer "sees" the troughs of the long waves, it is unable to generate small-scale roughness there, reducing the overall microwave reflectivity.

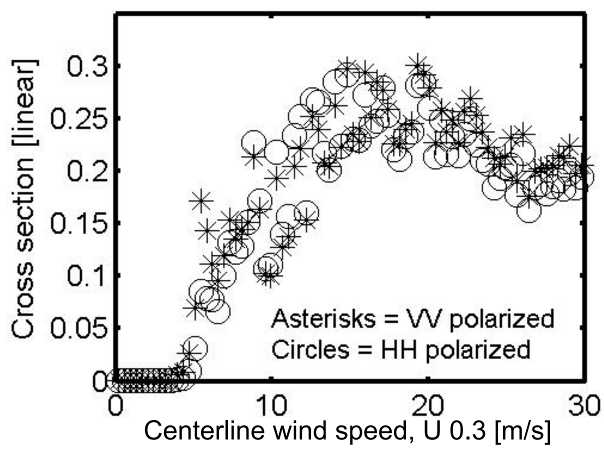

Figure 2. Microwave reflectivity from the ocean surface in strong winds, The maximum centerline wind speed (30 m/s) corresponds to a U10 of ~53 m/s. This figure appears as Figure 5 in Donelan et al. (2004).

II. Pressure-slope correlation in high winds

The results of the study show that the pressure was shifted significantly toward the windward face of the long wave, providing a large correlation between the pressure and the local slope (figure 3). The correlation over the wind range observed shows a strong dependence on U_{10} (figure 4).

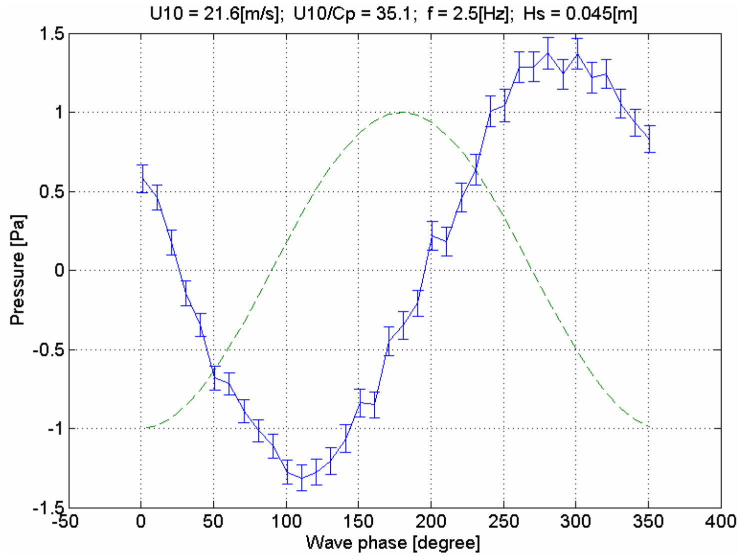

Figure 3. Pressure measured from the wave follower (blue- solid) conditionally averaged by long wave phase. Error bars show 95% confidence interval. U10 – wind speed at 10m height, U10/Cp – inverse wave age (Cp – wave phase speed), f – dominant frequency, Hs – significant wave height. Wind direction is from right to left.

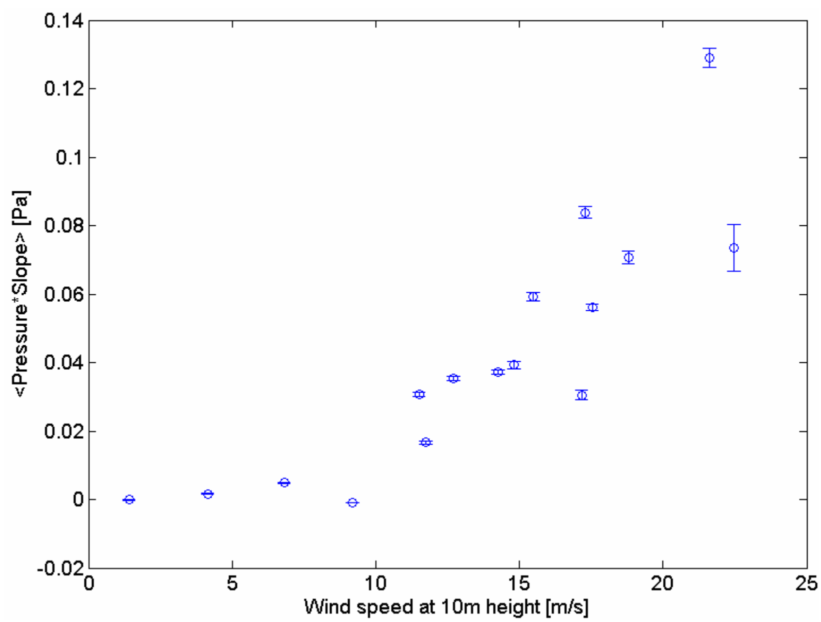

Figure 4. Pressure-slope correlation dependence on U_{10}, Error bars show 95% confidence interval

IMPACT/APPLICATIONS

We demonstrated the very clear saturation in the drag coefficient at wind speeds above 33 m/s and offered an explanation for this effect based on separation of the air flow from the crests of steep storm waves. A limit to the wind speed dependent drag coefficient had been deduced from energetic arguments in a hurricane (Emanuel, 1995), and our work clarifies the mechanism and points the way to eventual parameterization of the drag on the oceans in strong winds in terms of the predicted directional wave field and the surface (10 m) wind. This has resulted in a fundamental change in the understanding of air-sea momentum exchange in high winds. The drag coefficient curve resulting from this effort has been incorporated in recent hurricane and ocean mixing models. It has been shown to provide more realistic hurricane intensities and mixed layer responses than the traditional linearly increasing coefficient. Because of the wide range of applications that require specification of the air-sea drag, there has been a large impact of the revised formulation of the drag coefficient that resulted from this project.

REFERENCES

Donelan, M.A. and Pierson, W.J., 1987: Radar Scattering and Equilibrium Ranges in Wind-Generated Waves - With Application to Scatterometry. *J.Geophys. Res.*, **92**, 4971-5029.

Donelan, M.A., W.M. Drennan, and A.K. Magnusson, 1996: Nonstationary Analysis of the Directional Properties of Propagating Waves. *J. Phys. Oceanog.*, 26:9, 1901-1914.

Donelan, M.A., Haus, B.K., Reul, N., Plant, W.J., Stiassnie, M., Graber, H.C., Brown, O.B., and Saltzman, E.S., 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophys. Res. Letters*, Vol. 31, No. 18, L18306, doi:10.1029/2004GL019460.

Emanuel, K.A., Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52** (22), 3969-3976, 1995.

PUBLICATIONS AND PRESENTATIONS

Donelan, M.A., Haus, B.K., Reul, N., Plant, W.J., Stiassnie, M., Graber, H.C., Brown, O.B., and Saltzman, E.S., 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophys. Res. Letters*, Vol. 31, No. 18, L18306, doi:10.1029/2004GL019460.

Donelan, M. A., B. K. Haus and J. Zhang. Preliminary results from laboratory experiments on the Air-Sea Coupling Coefficients for sensible and latent heat in High Winds. CBLAST-Hurricane Science Meeting, 4-6 April, 2005, RSMAS/University of Miami, Miami, FL. http://www.aoml.noaa.gov/hrd/cblast/cblast4.html.

Coquet, F., Structure turbulente á la surface océanique et ses implications pour la méthode inertio-dissipative. Rapport de stage 2^{o} année. 2003.